Planar sandwich antennas for submillimeter applications[a)]

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A planar receiving antenna with a predictable pattern at submillimeter wavelength is demonstrated experimentally for the first time. It is single lobed and efficient, with a gain of approximately 8 dB at a wavelength of 119 μm.

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At wavelengths less than 1 mm it is difficult to couple radiation efficiently into devices such as diode mixers. Earlier work[1,2] has made use of tungsten filament antennas mechanically contacted to diodes. When used with reflectors such "cat-whisker" antennas can be highly directive and can thus provide good coupling.[13] However, the cat-whisker antenna is large, mechanically unstable, and unsuitable for replication into arrays. Moreover, as the wavelength of interest decreases, so does the optimal diode size; a mechanical contact to such small diodes becomes increasingly difficult. A need for *planar* submillimeter mixers has been recognized, and planar diodes as small as 2 μm in diameter have been constructed.[4] Ideally, these diodes shuld be integrated with planar evaporated metal antennas to provide a compact rugged structure into which submillimeter radiation could be efficiently coupled. However, planar antennas built until now have been somewhat unsatisfactory. They have not had high gain or predictable antenna patterns.[5,6] In earlier work[7] the causes of this difficulty were studied. There it was noted that a wire antenna lying on the surface of a dielectric has a poor gain. We can see the reason for this if we think of the antenna as a transmitting antenna. A wave excited on the antenna tends to travel at a velocity faster than light in the dielectric, causing the wave to radiate quickly into the dielectric. The effective length of the antenna, then, is very short, and its gain is low. Accordingly, it was proposed that antennas be constructed in "sandwich" form.[7] In this approach a planar antenna is fabricated on a planar dielectric substrate, and a second layer of dielectric, which we shall call a "superstrate," is then placed *over* the antenna. Now the antenna is *completely* encased in dielectric, and free-space antenna designs may be used after scaling for wavelength and impedance changes.[8] In the present communication we report good performance at 119 μm of an antenna based on this principle. We believe this is the first successful demonstration of a planar submillimeter antenna.

Our experimental device consists of a planar V receiving antenna combined with a small bismuth-film bolometric detector, as shown in Fig. 1. The V antenna is suitable for coupling applications because of its high-gain single-lobed pattern as well as its large bandwith.[9,10] It may be thought of as consisting of two long-wire antennas. Each wire has a conical pattern with a maximum at a certain angle θ from its axis. If the angle of the V is made 2θ, the two major lobes add in phase along the symmetry axis of the V, producing a large single lobe. The width of the arms of the V is made proportional to the distance from the vertex in order to reduce conductor loss and maintain constant characteristic impedance. The characteristic impedance depends on the angular widths of the arms and the angle of the V, while the gain depends primarily on the length of the arms. In this particular device the length of the arms is 560 μm, i.e., 10 wavelengths in the dielectric, the angle betwen the center lines of the arms is 32°, and the angular width of each arm is 10°. The calculated characteristic impedance is $302/n\ \Omega$, where n is the refractive index of the substrate/superstrate material.[7] Impedance measurements made on enlarged models at X band show that the driving-point impedance is close to the calculated characteristic impedance. In our case the dielectric is crystal quartz ($n_0 = 2.12$ [11]) 1 mm (17.8 dielectric wavelengths) thick, aligned with the optic axis parallel to the axis of the V. Thus, the driving-point impedance is 140 Ω. Our calculations for an antenna of the same electrical length in free space (details of which are too lengthy to be given here) give an estimated directivity of 16 dB. (We have also used X-band modeling to make measurements of half-power beam widths; using the approximate formula for directivity[12] $D = 27\,000/\theta_E\theta_H$, we obtain a larger directivity of 19 dB.) However, several effects cause the gain of the 119-μm antenna to be reduced. Those effects, with our estimates of their magnitudes, are as follows: conductor loss (1 dB), dielectric absorption (0.4 dB), reflection at dielectric interface (0.6

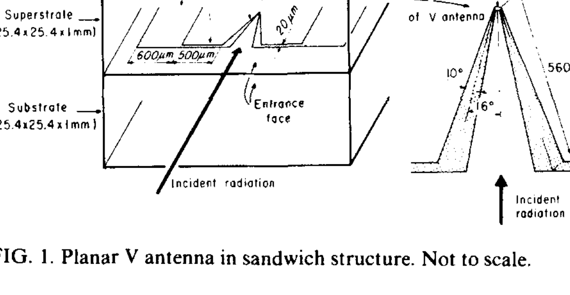

FIG. 1. Planar V antenna in sandwich structure. Not to scale.

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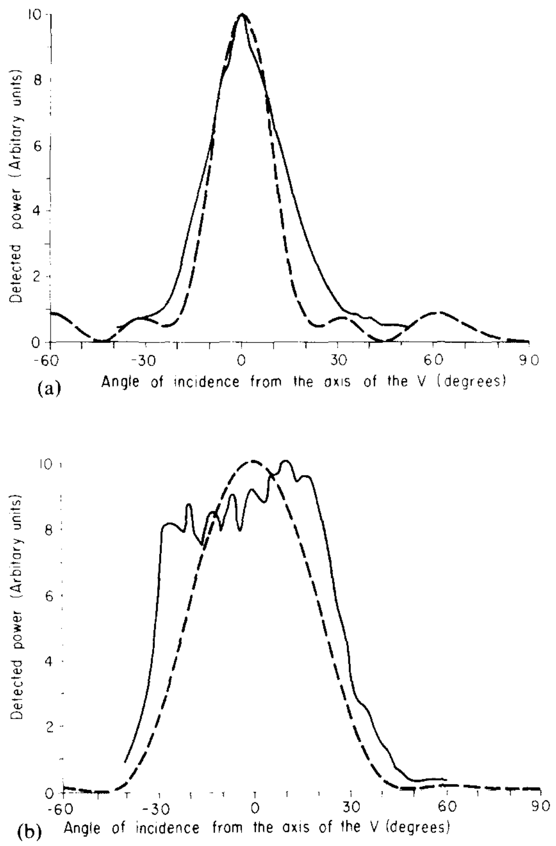

FIG. 2. Comparison of 119-μm antenna patterns with theory. Solid line is infrared pattern; dashed line is theoretical pattern of a thin-wire V antenna, modified to show the pattern expected after reflection and refraction at a plane quartz-air interface. (a) is for the E plane, (b) for the H plane.

dB), and refraction at dielectric interface (6.5 dB). Subtracting the above-mentioned reductions from the theoretical directivity gives a theoretically estimated gain of 7.5 dB.

By far the largest factor acting to reduce gain is refraction at the dielectric interface. If we think of the antenna as a transmitting antenna, the emerging rays refract away from the normal to the surface, spreading the beam. This loss could be eliminated by curving the dielectric face so that the rays would be normal to the surface, and not refracted.

The device shown in Fig. 1 was fabricated as follows. First, the silver antenna arms and dc connections, 65 nm thick, were deposited using a photolithographic lifting process. Then, a bismuth film was deposited everywhere, photoresist was placed over the apex of the V, and the bismuth film was removed elsewhere by sputter etching. The bolometer size is about $5\times4\,\mu$m and its thickness is made 55 nm, resulting in a dc resistance of 170 Ω, close to the antenna impedance. The measured temperature coefficient of resistivity $\alpha=\rho^{-1}(d\rho/dT)$ for our bismuth films is 3.3×10^{-3}. A quartz superstrate identical to the substrate is mounted over the device using a jig with nylon pressure-adjusting screws. The spacing between substrate and superstrate is determined approximately by observation of interference fringes. The entrance faces (the sides of the substrate and superstrate where radiation enters) were aligned within 1 μm by means of a microscope. Radiation for the measurements was obtained from a 118.8-μm methanol laser. When radiation is applied a 2.5-THz voltage appears across the bolometer, causing Ohmic heating and changing its dc resistance. A dc bias of 35 mV is applied to the bolometer and the laser is chopped at 257 Hz. Measurements of voltage at the chopping frequency across the bolometer are made with a phase-sensitive amplifier as a function of angle of radiation incidence or polarization.

The observed 119-μm antenna pattern for the E plane (the plane of the antenna) is shown in Fig. 2(a), and the H plane is shown in Fig. 2(b). These patterns indicate power delivered to the bolometer as a function of the angle between the axis of the V and the direction of radiation incidence. Also shown in Figs. 2(a) and 2(b) are the theoretical patterns of a thin-wire V antenna in air, modified to give the patterns expected after reflection and refraction through the plane quartz-air interface. The amplitudes of the curves are normalized with respect to their maximum values. The substantial agreement between these patterns justifies the assertion that the pattern of the planar sandwich antenna is predictable. The antenna also discriminates strongly between polarizations, favoring the E plane (in terms of received power) by at least 20 to 1.

In order to estimate the efficiency of the antenna we use the formula for the chopping-frequency voltage across the antenna-coupled bolometer,

$$v=\frac{\alpha V_B \lambda^2 I g}{4\pi\,|G(f)+j2\pi fC\,|},\tag{1}$$

where g is antenna gain, V_B is the bias voltage, I is the incident radiation intensity, and $G(f)$ and C are the thermal conductance and thermal capacity of the bolometer, respectively, the former a function of the chopping frequency f. In principle, this formula can be used to determine the gain from measurement of v. (The expression for effective area $A_e=\lambda^2 g/4\pi$ has been used.) The laser intensity I is measured with a Molectron P1-42 pyroelectric detector. Using the manufacturer's approximate calibration of this detector at 119 μm and estimating the other quantities appearing in Eq. (1), we find $g=7.9$ or 9 dB. Considering uncertainties in the parameters of Eq. (1) this result is consistent with the 7.5-dB gain estimated above.

It is important that the air gap between the substrate and the superstrate be small and that the entrance faces of the substrate and the superstrate be well aligned. We found that a 1-μm air gap is enough to cause a notch in the center of the H-plane pattern, reducing the gain at 0° by 30%. We also found that a 25-μm misalignment causes a similar notch. Even with the smallest possible gap and less than 1-μm misalignment the observed H-plane pattern [Fig. 2(b)] is wider than the theoretical pattern. This may be because of a remaining misalignment or a residual air gap due to the finite thickness of the antenna structure. Perhaps this air gap could be eliminated by "countersinking" the antenna into the substrate (i.e., by depositing the antenna in a groove etched in the substrate) or by filling the space with a sufficiently low-loss index matching material.

In summary, the "sandwich" technique allows fabrication of planar antennas with predictable patterns. If greater directivity is needed, a large increase could be obtained by shaping the quartz-air interface. More complex antennas and antenna arrays can be built in sandwich form. We are presently investigating the possibility of parallel-metallic-conductor submillimeter transmission lines based on the same princple.

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Field-ion microscopy of liquid-metal gallium

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Ionization of liquid gallium coated on a tungsten field-ion tip was investigated using a magnetic-sector atom probe. For the first time, both the energy distribution of ionized Ga and its critical energy deficit with respect to a tip potential were measured as a function of field and tip temperature. Without heating the gallium, a stable Ga^+ ion current of up to 10 μA was obtained from a small surface area of a tip with an energy distribution of less than 12 eV FWHM.

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Development of a focused ion beam of high brightness using liquid metal has attracted considerable interest because of its possible applications in microfabrication, microimplantation, and microprobes.[1–6] Although a few successful attempts in the practical applications have been reported so far[6] there is little information available on the basic physics of the ion formation from liquid metal. Making use of the improved magnetic-sector atom-probe field-ion microscope (FIM) which we have recently developed,[7,8] we have studied field ionization of gallium coated on a tungsten FIM tip. This investigation has produced some useful information on the ion formation from a liquid phase. In this letter we report for the first time the energy distributions and the critical energy deficits of Ga^+ and Ga^{++} ions field evaporated from gallium on the surface of a tungsten emitter. These measurements also enable us to determine the binding energy of a Ga atom on a Ga surface.

The magnetic sector atom probe[7] is a combination of an FIM with the atomic resolution and a momentum analyzer with single-particle-identification capability. The selection of a single surface atom or a very small surface area to be analyzed is made by placing the desired area of the image of the FIM tip over a probe hole at the center of the channel plate-screen assembly through manipulation of the tip orientation. Subsequently, the surface area of interest is field evaporated by temporarily increasing the field strength at the tip. Only ions coming through the probe hole enter the filter-lens-type of retarding potential analyzer[8] and the second-order 60° magnetic-sector lens (Fig. 1). The retarding potential analyzer permits us to measure the energy distribution of field-evaporated ions and their energy deficits ΔE with respect to an emitter potential V_{tip}, with an accuracy of 100 meV out of 2000 eV primary energy ($E/\delta E \simeq 20\,000$). The magnetic-sector lens below the retarding potential analyzer displays the momentum spectra of the incoming ions on the 75-mm-diam chevron double-channel plate-screen assembly, with a mass resolution ($M/\delta M$) of over 1000, sufficient to separate any isotopes and their hydrides in the mass range 0.1–210 amu. The unique feature of the magnetic-sec-